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THE GEM EXTENSION SATELLITE TOUR: GALILEO'S MISSION ACROSS THE MILLENNIUM

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A one year follow-on mission to the Galileo Europa Mission (GEM) has been proposed. This extension to GEM begins in October 1999 and consists of six encounters, the first two overlapping with the last two encounters in GEM. The extension will augment GEM observations, and also offers the possibility of simultaneous fields-and-particles experiments coordinated with the Cassini spacecraft as it swings by Jupiter in December, 2000.

INTRODUCTION

An extension to the current Galileo Europa Mission (GEM) has been proposed that will extend GEM by fifteen months. The extended GEM mission (called GEM-ex in this paper for brevity) is the successor to both the Galileo prime mission and the Galileo Europa Mission. As a third generation tour GEM-ex will continue to follow stategies similar to its predecessors, but its objectives will be scaled back.

The final three months of GEM contain three encounters. These final three encounters of GEM are with Callisto (on September 16, 1999) and Io (on October 11 and November 26). Once more for the sake of brevity we use abbreviations, and so to indicate these satellite encounters we designate them as C23, I24, and I25 respectively, where the C indicates Callisto, the I indicates Io, and the numerals represent the orbit number in which the encounters occur. Thus the final encounter of GEM occurs at Io on Galileo's 25th orbit of Jupiter. The two Io encounters of GEM are designed for high-resolution imaging and occur at altitudes of 500 km and 300 km respectively, distances close enough to the surface of Io to possibly encounter volcanic ejecta. The radiation environment around Io is very severe and spacecraft passages near Io are considered hazardous to the spacecraft's well-being. Moreover the spacecraft is ten years old and its resources strained. With this provenance GEM-ex must build its tour.

THE PREVIOUS TOURS

GEM-ex extends the sequence of satellite encounters begun in the prime mission. The prime mission was the first tour of its kind -- a gravitationally-assisted sequence of encounters between satellites orbiting a primary. That mission consisted of ten satellite encounters in eleven orbits around Jupiter between January 1996 and December 1997[1]. By shaping the trajectory of each subsequent orbit around Jupiter, this sequence of encounters permitted mission designers to undertake a tour of the Jupiter system with nearly two orders of magnitude less propellant than would otherwise have been required. The prime mission concluded December 1, 1997 and, within the limitations of its low-gain antenna,

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accomplished all of its objectives.

GEM followed the prime mission and is underway as of this writing (July 1999). It consists of fourteen satellite encounters in fourteen orbits around Jupiter between December 1997 and December 1999[2]. GEM has returned a wealth of observations and measurements, but its accomplishments have been more limited than the prime mission (to be fair, GEM's resources are also more limited). At the time of this writing only seven of ten encounters have successfully returned to Earth the sequence of high-resolution observations scheduled for each encounter. In each case an on-board fault shutdown a spacecraft system necessary for continuing the observations. In each case the spacecraft fault occured at or near perijove, indicating that some spacecraft components may be approaching end-of-life (see the discussion below on radiation exposure).

SCIENCE OBJECTIVES

The major science objectives of GEM-ex can be separated into roughly three areas of investigation: magnetospheric science (fields and particle measurements around Jupiter and its satellites), atmospheric science (observations of Jupiter), and planetology (observations of satellite morphology and measurements of composition and gravity). Galileo's payload instruments continue to function as designed, albeit with some degradation. None of the degradations are life-threatening. The payload consists of eleven experiments, described in Table 1[3].

Table 1

THE INSTRUMENTS AND THEIR FUNCTIONS

Instrument	Function
Magnetometer	Magnetic field characterization
Plasma Instrument	Analyses low energy plasmas
Plasma Wave Instrument	Analyses radio and plasma waves
Energetic Particles Detector	Measures distributions and energies of ions and electrons
Heavy Ion Counter	Measures distributions of large, ionized atoms
Dust Detector	Measures distribution and energy of dust particles
Radio Frequency Subsystem	Celestial mechanics and atmospheric composition measurements
Solid State Imaging Camera	Visible wavelength observations
Near Infrared Mapping Spectrometer	Measures heat emissions and chemistry / mineralogy
Photopolarimeter-Radiometer	Measures temperature profiles
Ultraviolet Spectrometer	Measures atmospheric and Io torus composition

Investigators on GEM-ex placed high priority on fields-and-particle measurements. Remote sensing observations will continue to be important, but the science criteria for tour selection focused mainly on fields-and-particle goals. Therefore GEM-ex maximizes science return from the fields-and-particles experiments, while simultaneously accomodating observations from the remaining experiments and satisfying mission-imposed constraints.

TOUR DESIGN

Procedure

Designing this tour consisted of three steps, where each succesive step calculated greater detail than the preceding step. In step one, a two-body conic approximation method was employed to select possible flyby conditions at each satellite in a series of satellite encounters. This method targetted successive satellites in the encounter series. Starting with the initial conditions of the spacecraft at the current-satellite, each successive upcoming satellite was targetted until completing the tour. Orbits were connected at common encounter times with three degrees of freedom. Occasionally a deterministic maneuver would need to be introduced at apojove in order to satisfy end conditions at the target satellite. Upon completion of this conic approximation, a cursory outline of the final tour was available for inspection.

Trajectory shaping is possible because of the barycentric velocity imbalance induced at each satellite encounter. The governing relation determining the magnitude of the spacecraft's velocity change in jovicentric space at each encounter is determined from the following relation, where V_∞ represents the velocity of the spacecraft at infinity, μ equals the product of the universal gravitational constant G and the mass of the encountered body, and r_p represents periapse radius.

$$\Delta V = \frac{\dfrac{2\mu}{V_\infty^2 r_p}}{1 + [\mu / (V_\infty^2 r_p)]} V_\infty$$

The second step in the design introduced detailed constraints into the conic approximation. An optimization procedure was invoked to adjust spacecraft state at each flyby in order to stitch together the individual orbits with six degree of freedom continuity, all subject to flyby constraints and minimization of the total tour ΔV[4].

The third design step numerically integrated a trajectory using the optimized inputs from step two. The specific inputs included spacecraft state at each flyby and the deterministic ΔV's applied at one or more apojove locations. Each prospective tour, once completed, had to demonstrate closure with respect to the mission goals and science objectives. If analysis indicated the tour to be unsatisfactory, the process was begun anew (redesign efforts began from the two-body formulation since significant adjustments to an integrated tour were not possible to accomodate).

Constraints on the Design

Science Planning

The Deep Space Network is over-subscribed in January and February, 2000 by other deep space missions. The paucity of DSN station coverage for GEM-ex in those months will appreciably reduce the science return from Galileo.

The low altitude, latitude diverse, light-side trajectories at I24 and I25 were highly valued and specified as a priority by the project. Specifically, in the nominal GEM tour, the Io closest-approach altitudes were designed to be 500 km and 300 km at latitudes of 17° S and 80° S, respectively. Those encounter geometries, once devised, became *de facto* constraints for the GEM-ex redesign because of the valuable and focused science to be gained at those encounters. Therefore any tour-attachment strategy was subject to preserving as much as possible of the original GEM design subject to operational constraints..

An important objective for the magnetometer investigators in GEM-ex is the measurement and characterization of Europa's internal magnetic field. A field was indeed characterized during the prime mission, but a key measurement was missed at Europa on the sixth orbit (E6) when the magnetometer malfunctioned. (The measurement would have indicated whether Europa's field was intrinsic or induced by Jupiter.) GEM-ex offers the possibility of repeating this measurement. The measurement must occur at an altitude less than 400 km when Europa is located between 0° and 60° west Jupiter longitude.

Another science goal in GEM-ex arises from a unique *ad hoc* opportunity which bounds the design. In December, 2000 the Cassini spacecraft swings by Jupiter enroute to Saturn. An operational Galileo spacecraft at that time would permit simultaneous fields-and-particles experiments coordinated with Cassini. Ideally, measurements by one spacecraft would be obtained from within the Jupiter bowshock while the other spacecraft obtained measurements from beyond, and *vice versa*.

Environmental Degradation

A torus of dense plasma surrounds Jupiter in a belt from approximately 3 R_J to 11R_J, with maximum intensity at about 6 R_J. Exposure to the high energy particles in this region degrades the health of the vehicle, so repeated deep passages through the torus were delayed until as late as possible in GEM (Galileo passed through this region once when it arrived at Jupiter in December, 1995). One constraint in the prime mission was limiting radiation exposure to a maximum of 150 krads (*i.e.* the spacecraft builders conservatively judged the spacecraft to be hardened to radiation damage for levels not exceeding 150 krads). The dosage from a single perijove passage at the distance of Io's orbit (~30 - 40 krads) is three to four times greater than the dosage received at the distance of Europa's orbit and is one of the primary reasons for placing the Io encounters at the end of GEM. The cumulative dosage absorbed by Galileo after the I25 encounter is predicted to be approximately 370 krads. For comparison, the dosage after E11 (end of prime mission) totalled 136 krads and by E19 had risen to 224 krads. (An exposure intensity of 1 krad each second is equivalent to 0.1 watt of energy released within each gram under exposure. The actual intensity encountered by Galileo in the Io environment is much less -- on the order of 0.25 rad/s.)

By March, 1998, having reached the end of the prime mission and begun GEM with no significant (or even apparent) radiation degradation, the Galileo project considered testing the limits of Galileo's endurance. With an assumed 3σ radiation tolerance level of 150 krad, the spacecraft could conceivably continue to function (with 1σ certainty) at exposure levels of 450 krad or beyond. Hence the proposal to operate Galileo into the year 2000.

Tour Continuity

The GEM design abandoned Galileo in an inclined, 39 day period orbit with perijove at 5.7 R_J thereby placing the spacecraft, and any extension to GEM, at considerable risk. The risk to prolonging the tour is two-fold: the high radiation environment near Io, and the absence of suitable orbital characteristics. The I25 flyby as designed places Galileo in an orbit with an unfavorable inclination for achieving future satellite gravitational assists (2.1° with respect to the Jupiter mean equator, or JME). This inclination is one of the obstacles to prolonging the tour. That is, any design of a tour beyond I25 suffers maximally from spacecraft trajectories inclined to the Jupiter ecliptic, whereas the converse is as equally beneficial.

Analogous to GEM's design with respect to the prime mission, we were faced with the problem of finding an attachment point for GEM-ex with respect to the extant GEM mission. A trivial location for the attachment is a point following the I25 encounter, but this location would require a maneuver to bring Galileo back into the Jupiter ecliptic. Therefore to tackle this problem we must decide whether to implement a (large) inclination-correcting maneuver following I25 (say at apojove), or to backup the attachment point of GEM-ex into GEM and redesign several of GEM's last orbits in order to prevent Galileo from ever leaving the local ecliptic.

One significant problem with a post-I25 attachment is the cost it imposes upon the mission. The magnitude of the maneuver to eliminate the out-of-plane component can be roughly estimated from the following relation (valid only for circular orbits and small inclinations):

$$|\Delta V| = 2V \sin(I/2), \text{ where I is inclination and V is velocity.}$$

This relation yields a value of 58 m/s to correct an inclination of 2.1°. More detailed calculations have determined the velocity change at apojove to be from 20 - 35 m/s, depending upon the orbital characteristics we are seeking to match.

The strategy of backing-up the attachment point was expected to be optimal for propellant consumption. Therefore we examined a redesign of the last two orbits of GEM, using a point at the apojove between C23 and I24 as the attachment to GEM-ex. With this strategy one of our designs determined the following closest approach parameters at I24 and I25. The I24 altitude remained at 500 km (*i.e.* no change from GEM) but its latitude and longitude moved to 15° S and 228° W (cf. 17° S, 224° W in GEM). The I25 altitude increased to 2504 km (cf. 300 in GEM) while the closest-approach latitude and longitude shifted to 61° S and 27° W (cf. 80° S, 57° W in GEM). The times of the encounters did not differ significantly between these tours. This particular design placed Galileo into a post-I25 orbit with an inclination of 0.9° JME and required a deterministic propellant expenditure of 18.1 m/s to complete GEM-ex (all of it spent in a single maneuver at the apojove between I24 and I25). The nominal GEM apojove maneuver at this location requires 8.6 m/s, so the net increase in deterministic propellant consumption to extend GEM with this nearly-optimal design is approximately 10 m/s.

This representative redesign of orbits 24 and 25 (and other designs similar to it) was satisfactory for navigation purposes, but the Galileo Planetary Science Group was not satisfied with its potential science return *vis-a-vis* the existing GEM tour (especially because of the work already invested in planning for those GEM encounters). Specifically, the polar flyby at I25 was very appealing to the science community. Thus the I24-I25 redesign strategy was dropped from further consideration.

We briefly considered attaching the follow-on tour one orbit later, at the apojove between I24 and I25. This option was quickly discarded since, as in the previous case, the I25 science goals were unachievable. In practice, coming as they do at the end of the GEM tour, the two Io encounters have to be designed as a pair in order to satisfy the Io science constraints.

Having exhausted earlier attachment points, the practical synthesis was to join the extension to GEM at the apojove following I25 and implement an inclination-correction maneuver. Thus, an attachment ΔV on the order of 30 m/s was accepted as the cost in deterministic propellant consumption in order to retain the nominal Io aimpoints of the GEM mission. Whether Galileo can sustain this cost is addressed in the following sections.

Propellant Availability

Propellant is a scarce, consumable resource. As of June 1, 1999 the Galileo propellant margin at end-of-mission (*i.e.* end of GEM on December 1, 1999) was equivalent to 68 m/s. This means that at a 90% level of certainty, no less than 68 m/s of velocity control will be available to GEM-ex after December 1, 1999 for trajectory shaping, attitude maintenance, and navigation. An appreciable fraction of this propellant must be allotted for a probable inclination-correction maneuver (~30 m/s). Thus the balance of the navigation effort during GEM-ex will be constrained to a budget of approximately 38 m/s (90th centile). In comparison, the statistical maneuver propellant expended to navigate the prime mission totalled 32 m/s for ten encounters, and the equivalent figure spent in GEM to June 1, 1999 equals 13 m/s (for nine encounters). (Statistical maneuver propellant includes propellant expended on events like attitude maintenance and path-correction, but does not include pre-determined maneuvers like an inclination-correction.) The statistical propellant quantities just cited, while labelled statistical, are nevertheless well-determined empirical values since they now represent past events.

Summary of Constraints

The GEM-ex tour, a proposed GEM extension with a goal of coordinating observations with Cassini at Jupiter, must satisfy the following constraints. The tour must maintain continuity with GEM and preserve the GEM Io aimpoints, target to E26 to satisfy the magnetometer experiment and subsequently satisfy science objectives at the remaining encounters, reach perijove on or about December 30, 2000, mininmize radiation dosage (no greater than ~450 krads), and operate the spacecraft for one year on a ΔV budget of 68 m/s (90th centile). The GEM-ex propellant budget may appear adequate judged by past experience, but the operational environment and flyby geometries in GEM-ex will be the most severe yet encountered by Galileo.

Topics of Raising Perijove/Apojove and Increasing Period

The integrity of GEM-ex depends on spacecraft health, and in the orbital environment of Io, the major threat to spacecraft health is radiation exposure. So the GEM-ex design became a race between calendar time and accumulated dosage.

The GEM-ex strategy proposes operating the spacecraft until a dosage of ~450 krads is attained (roughly three times the conservative limit of the prime mission). Nevertheless, at 40 krads per perijove and with the nominal post-I25 orbit period equal to 39 days, subsequent repeated perijove passages in the vicinity of Io's orbit rapidly subject Galileo to an overdose of radiation. Thus a goal for GEM-ex is to immediately begin raising spacecraft perijove (or failing that, increase its orbital period) in order to minimize radiation-induced degradation during the subsequent year.

The elegent method for preserving spacecraft health is to rapidly raise spacecraft perijove and return Galileo to a prime-mission-like orbit. The expense of this choice is prohibitive. The ΔV necessary to raise perijove from Io (5.7 R_J) to Europa (9.2 R_J) with a single burn is 460 m/s.

The alternative strategy free from deterministic ΔV costs (except for an inclination correction) minimizes radiation exposure by increasing orbital period. Perijove remains almost fixed (it actually rises slowly) but the frequency of perijove passages decrease as the orbit period increases. We have designed a tour with only four perijove passes between November 26, 1999 (I25) and January 1, 2001. The total dosage absorbed by the spacecraft equals about 450 krads and therefore the spacecraft's chances of survival until undertaking the joint observations with Cassini are in accord with the GEM-ex model.

The GEM Extension Tour

Tour Overview

The objective of finding an extension for GEM subject to the constraints already discussed was achieved. We define its beginning to be October 1, 1999 at the apojove preceding I24 (the computational attachment point of GEM-ex to GEM (*i.e.* GEM and GEM-ex overlap without major differences for two orbits)). The new tour consists of four new encounters: an inbound Europa (January 3, 2000), an outbound Io (February 22), and two inbound encounters with Ganymede (May 20 and December 28). The semi-major axis of each successive orbit is significantly greater than the orbit preceding it. Science observations, while limited, satisfactorily address all scientific goals.

The extension tour is plotted in Figure 1 and summarized in Table 2. The trajectory in Figure 1 is projected onto a plane normal to Jupiter's pole and is shown in a Sun-Jupiter-fixed orientation, where the direction of the Sun is toward the top of the figure. Motion occurs in a counter-clockwise direction. Representations of the orbits of Io, Europa, Ganymede, and Callisto, as well as three arcs that identify radial distance from Jupiter are also included in the figure.

As of June 1, 1999 the Galileo propellant margin on October 1, 1999 is equivalent to 84 m/s. Propellant margin has increased since the earlier discussion because now we decree the GEM end-of-mission to occur two months earlier (on October 1, 1999). I24 and I25 have been absorbed into GEM-ex, and consequently the estimated available-propellant figure corresponding to the earlier 38 m/s rises to 57 m/s.

Table 2
THE GEM Extension TOUR

Encounter	Date	Encounter Location	Altitude (km)	Latitude (°)	Pre-enc Period (d)	Perijove (R_J)	Pre-enc Inclination (deg JME)
I24	Oct 11 99	Outbound	611	4.5 N	26	5.5	0.1
E25a	Nov 25 99	Inbound	8518	62.5 N			
I25	Nov 26 99	Outbound	300	76.6 S	46	5.7	0.4
E26	Jan 3 00	Inbound	374	46.3 S	39	5.8	0.7
I27	Feb 22 00	Outbound	200	18.3 N	49	5.9	0.6
G28	May 20 00	Inbound	900	13.8 S	89	6.7	0.2
G29	Dec 28 00	Inbound	1000	14.8 S	224	8.3	0.7

Deterministic $\Delta V = 32.4$ m/s

Flyby Characteristics

The Io campaign at the tail-end of GEM (or the start of GEM-ex) provides two close Io encounters and one intermediate non-targetted encounter with Europa (on November 25). The I24 flyby is a low altitude, low latitude, lightside encounter which will observe known, active volcanic regions. A low altitude, high latitude, darkside flyby is retained at I25 to accomodate remote sensing, geodesy and magnetometer experiments. Because the I25 flyby is nearly polar, remote-sensing observations of lighted terrain will be possible even at closest approach. (This flyby cranks the outbound trajectory into an orbit with an inclination of 2.1° JME.) Both Io encounters are outbound geometries, although necessarily occuring close to perijove. Minor changes from the original I24 and I25 aimpoints were unavoidable in the redesign, with the result that the Io encounter conditions changed in minor ways. At I24 the GEM altitude rose from 500 km to 611 km in GEM-ex and the latitude shifted from 17° S to 5° N. At I25 the altitude remained unchanged but the latitude shifted from 80° S to 77° S. The encounter geometries for these flybys, as well as for the following four flybys, can be viewed in Figures 2a through 2f.

Note the northward shift of both the redesigned closest-approach spacecraft groundtracks for I24 and I25. This migration contributed significantly to a reduction in the magnitude of the inclination-correction maneuver that we have repeatedly discussed (by 11 m/s). This inclination-correction maneuver, now a feature of GEM-ex, removes the out-of-plane component from Galileo's orbit and returns the spacecraft into an orbit close to the Jupiter ecliptic. The magnitude of the maneuver is 22.4 m/s and occurs on December 15, 1999 at the apojove immediately following I25.

The Europa non-targetted flyby preceding I25 (E25a) occurs over the lightside at an altitude of 8518 km and with a phase angle conducive to global imaging opportunities. In the GEM design, this encounter was arbitrarily constrained to 10,000 km. By allowing the minimum altitude to sink lower in GEM-ex we were able to mitigate the up-stream consequences of even the (modest) changes applied to the I24 encounter. Without this flexibility at Europa the magnitude of the deterministic maneuver at the preceding apojove (between I24 and I25) would have risen to 10.5 m/s from 8.6 m/s

GEM-ex, unlike the prime mission and GEM before it, will find itself unable to return approximately one gigabyte (one tape-recorder-load) of data before the subsequent encounter (for the I25 and E26 encounters). This shortfall is partly due to short period orbits, but largely due to the reduced DSN station coverage extended to GEM-ex in January and February, 2000. This constraint limits retrievable observations at I25 and severely limits them at E26. In response, remote sensing observations at E26 will be curtailed and E26 encounter science will place primacy on downlink-friendly fields-and-particles experiments.

The radiation mitigation strategy of the tour is relaxed for one revolution in order to perform the magnetometer experiment at Europa. Europa, the least massive of the Galilean satellites, is also the least effective for orbit pumping, so it would not have been revisited in GEM-ex had it not been for the magnetometer objective. This experiment will take place on Janurary 3, 2000 at an altitude of 374 km, latitude of 46° S, true anomaly of -81°, and Jupiter west longitude of 2.4°.

The content of Figure 3 illustrates the significance of the E26 encounter[5]. The figure shows the three spherical components of the Europa magnetic field (B) and the total magnitude. The integers across the top of each graph in the figure represent satellite encounters. Thus the number 26 represents the E26 encounter. The asterisk superscript attached to 26 indicates that the encounter has not yet occured (as does the dashed vertical line beneath the 26*). Solid vertical lines in the figure represent past flybys, and dotted vertical lines indicate that no data was acquired at that respective encounter. The ordinate scale is measured in gauss. The uniqueness of the E26 sample space relative to all other Europa encounters is evident in the figure (except for E6 which was lost).

To extract as much energy as possible from Europa to pump the spacecraft orbit, Galileo passed behind Europa (relative to Europa's local velocity vector). For an inbound encounter this geometry yields a darkside approach to the satellite. Darkside encounters normally are not desirable for imaging purposes, but for this encounter the lighting is almost irrelevent since the downlink data rate is severely reduced (averaged over the post-E26 orbit). So retrieving large quantities of captured data from the tape recorder *a posteriori* will not be possible in any event. Nevertheless real-time (and some recorded) data acquired by the fields-and-particles instruments will be returned at levels satisfactory for those experiments.

The E26 encounter pumps-up Galileo's orbit by 10 days into a 49 day period. The equivalent ΔV boost to the spacecraft is 289 m/s relative to Jupiter. Spacecraft periapse radius rises from 5.7 R_J to 5.8 R_J.

The next encounter, labelled I27, is an outbound encounter with Io and occurs on February 22, 2000 at an altitude of 200 km and latitude of 18° N. This low, equatorial flyby increases the orbit period by 40 days, increases the spacecraft velocity by 761 m/s, and raises periapse radius to 5.9 R_J. Because this encounter is outbound, the orbit pumping technique provides a lightside encounter with geometry favorable for remote sensing. Moreover by March, average telecommunication rates have improved and the orbit period has increased, so a full tape load of accumulated data can be returned. Note that the spacecraft trajectory shown in Figure 2d passes Io on the farside, relative to the viewpoint of the observer.

Two encounters follow I27: both target to Ganymede. Similar to the I24 and I25 encounters, repeated encounters with a single satellite may be achieved using either resonant or non-resonant transfers. Resonant transfer paths are defined to be transfers between two flybys of the same satellite for which the orbital period of the transfer orbit is very nearly equal to *n* times the period of the satellite (where *n* is an integer). Thus, a resonant transfer will result in a pair of flybys that either occur both inbound or both outbound with respect to the primary. A non-resonant transfer orbit refers to all other transfer orbits. Generally, in order to achieve latitude diversity between successive flybys, some ΔV will be required to perturb the groundtrack (for any type of transfer orbit).

The G28 and G29 encounters are both inbound and represent a resonant transfer. Latitude diversity at the Ganymede flybys is a low priority and so additional ΔV is not expended for this purpose. Ganymede's purpose is to accelerate orbit pumping and increase period. With two flybys the goal is accomplished.

The characteristics of each flyby are almost identical. Both encounters are darkside flybys, a geometry limiting high-resolution imaging. The G28 encounter occurs May 20 at an altitude of 900 km and latitude of 14° S. The change to the orbit is 135 days and 485 m/s, resulting in a 224 day period. Periapse radius rises to 6.7 R_J. The G29 encounter occurs December 28 at an altitude of 1000 km and latitude of 15° S. This encounter increases the spacecraft velocity by 506 m/s and sends Galileo galumphing-off into interplanetary space, leaving the Jupiter sphere-of-influence (672 R_J) in July, 2001. Galileo will thereafter remain in a solar orbit adjacent to Jupiter, on the sunward side, for the indefinite future. Figure 4 traces Galileo's trajectory relative to Jupiter for more than six years -- the entire Galileo mission at Jupiter. (The trajectory illustrated in Figure 4 equals a distance of 700×10^6 km, which coincidentally is appoximately the Sun-Jupiter distance.)

Cassini Phase

The joint observations with Cassini will occur between December 15, 2000 and March 12, 2001. At the time of Cassini's closest approach to Jupiter on December 30, 2000, Galileo is located deep within Jupiter's magnetosphere at at distance of 8 R_J and Cassini is located outside the bowshock at a distance of 150 R_J. The bowshock wave is about mid-way between the two spacecraft at approximately 75 R_J. Two months later the relative positions of the spacecraft will have reversed. Galileo (250 R_J) will be outside the bowshock region and Cassini, downstream from Jupiter (~600 R_J), will have crossed over the diverging bowshock wave into the magnetotail. See Figure 5. This figure illustrates the relative positions of the magnetopause, bowshock wave, Galileo and Cassini, as well as the historical paths followed by the Voyager spacecraft.

Operational Considerations

Our calculations indicate that sufficient propellant will remain for Galileo to complete GEM-ex. The quantity of deterministic propellant required in GEM-ex (including the Io attachment portion) is 32.4 m/s. Most of this is burned at two locations: the apojove preceding I25 and the apojove preceding E26. In addition we estimate that the statistical propellant spent for navigation purposes (attitude and trajectory adjustments) will not exceed 44 m/s. Therefore at the 90th centile, we expect no less than 8 m/s of ΔV capability to remain at the nominal end of GEM-ex. The margin for error in GEM-ex is low however, and a single spacecraft malfunction at the time of a critical maneuver will likely mark the end of tour operations (insufficient propellant will remain to return the spacecraft to the nominal trajectory).

The monotonic increase of radiation absorption since the beginning of the prime mission is apparent in Figure 6. Radiation exposure after C20 escalates because this period represents the pump-down phase of GEM. Perijove distances decrease until they approach the orbit of Io and then remain at approximately that radius until the end of GEM-ex. The perijove distances in the figure represent the true distances that occur during the Jupiter flybys and not osculating perijove radii. Radiation dosages are calculated assuming that the spacecraft is an aluminium sphere with a shielding of 2.2 g/cm^3.

Using 450 krad as a guideline rather than a firm constraint for the GEM-ex upper limit, the tour we have designed yields a cumulative dosage of 480 krads on January 1, 2001, the time of the joint observations. Thus we expect, at a 1σ level of certainty, that Galileo will continue to function into 2001 and will achieve the planned rendezvous opportunity with Cassini.

CLOSING REMARKS

GEM-ex is a proposed extension of the Galileo Europa Mission (which was itself a follow-on mission from the Galileo prime mission). GEM-ex is a resource-limited tour, but a suitable design has been fashioned which extends GEM by one year and achieves all project goals. In particular, Galileo will be in a position to coordinate simultaneous fields-and-particles experiments with Cassini as it swings by Jupiter in December, 2000. Note that both GEM and GEM-ex have been made possible in their turn by the efficient husbanding of Galileo's resources during the preceding tour(s). The likelihood of this tour regres continuing beyond GEM-ex is remote since Galileo escapes from Jupiter on the last orbit of GEM-ex, and will thereafter remain in interplanetary space with most of its on-board resources exhausted.

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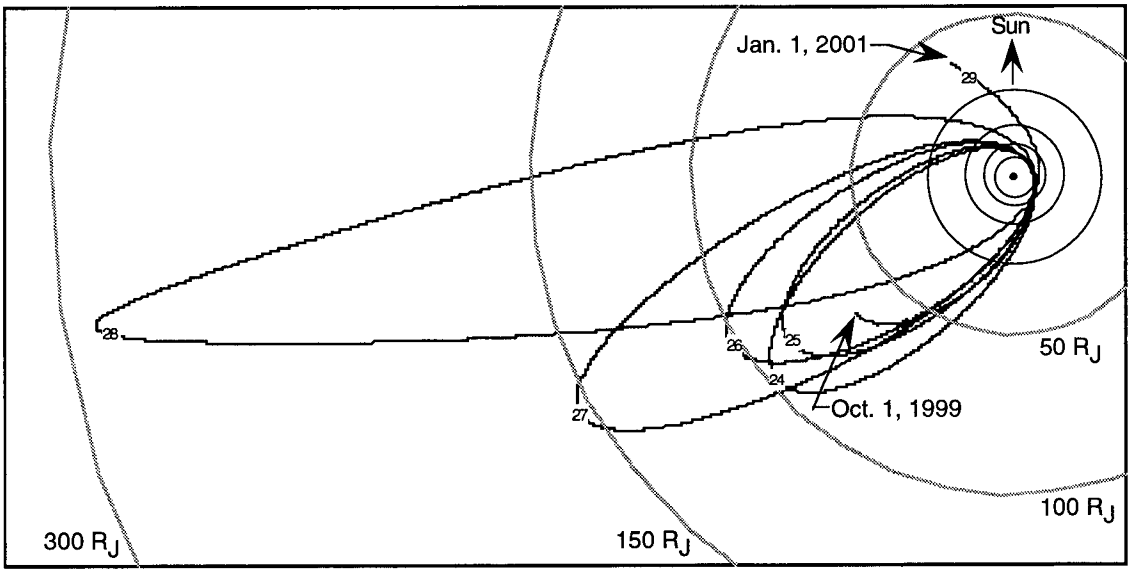
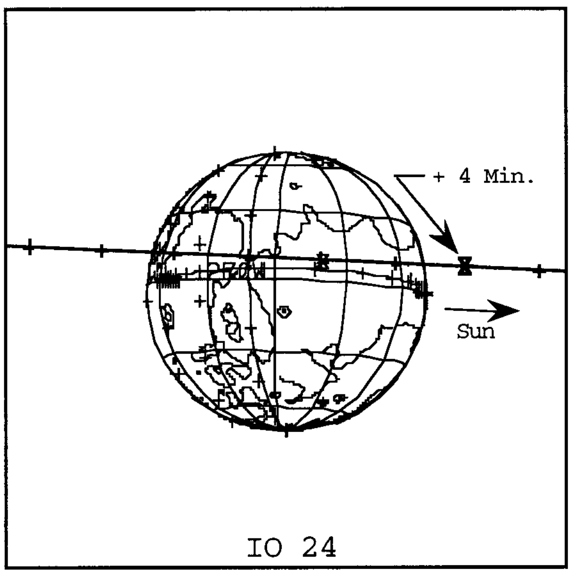
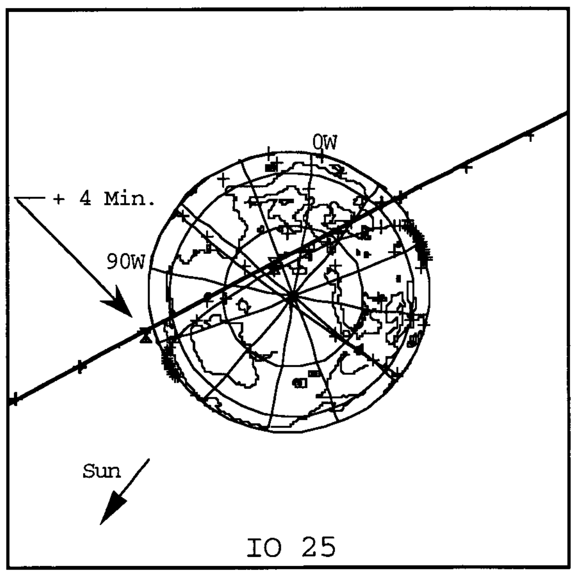


Orbit numbers denote postion near apoapsis (except 29) following same numbered satellite encounter

Figure 1 GEM-ex Orbital Tour





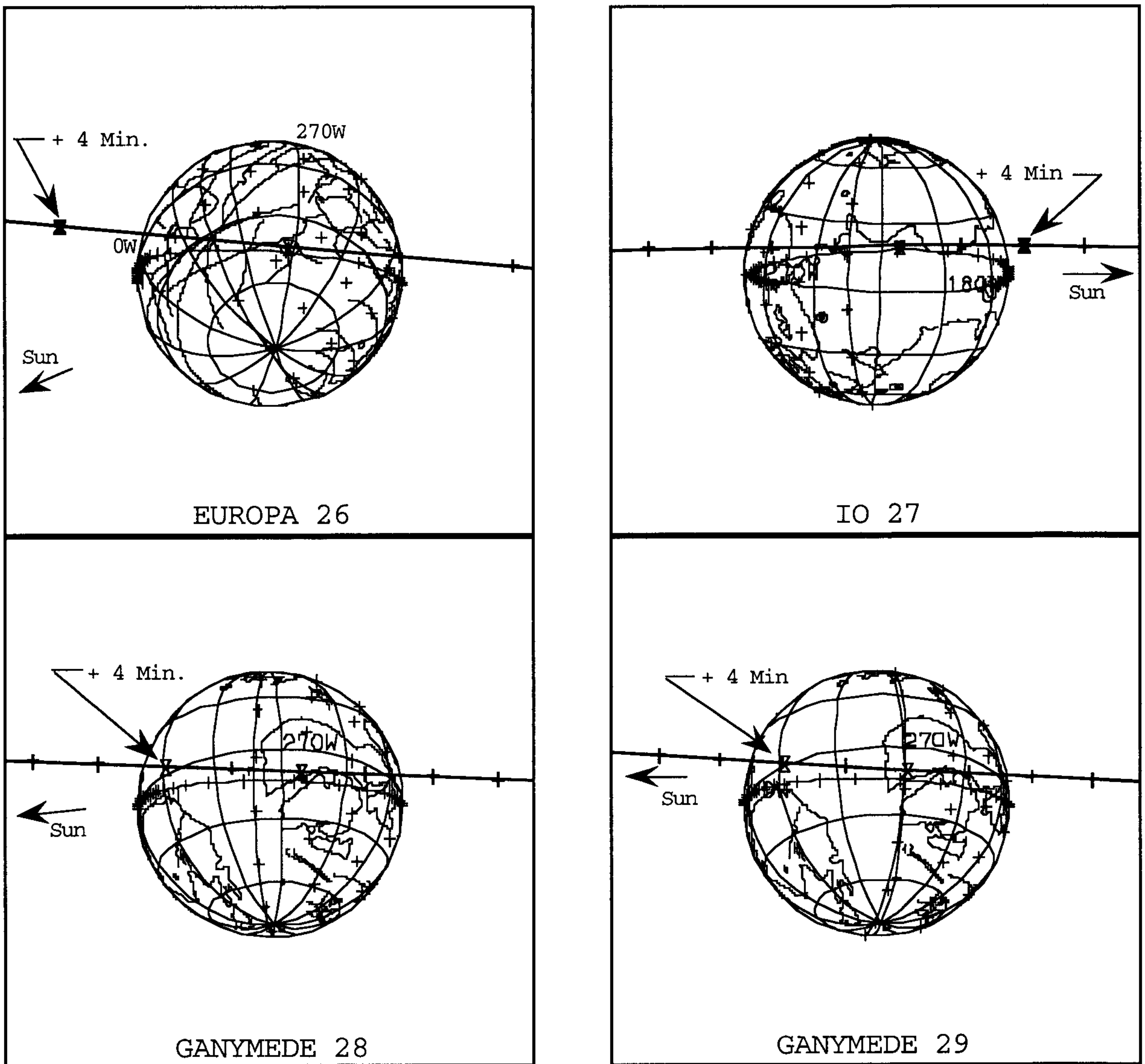


Figure 2a - 2f GEM-ex Satellite Encounter Geometries

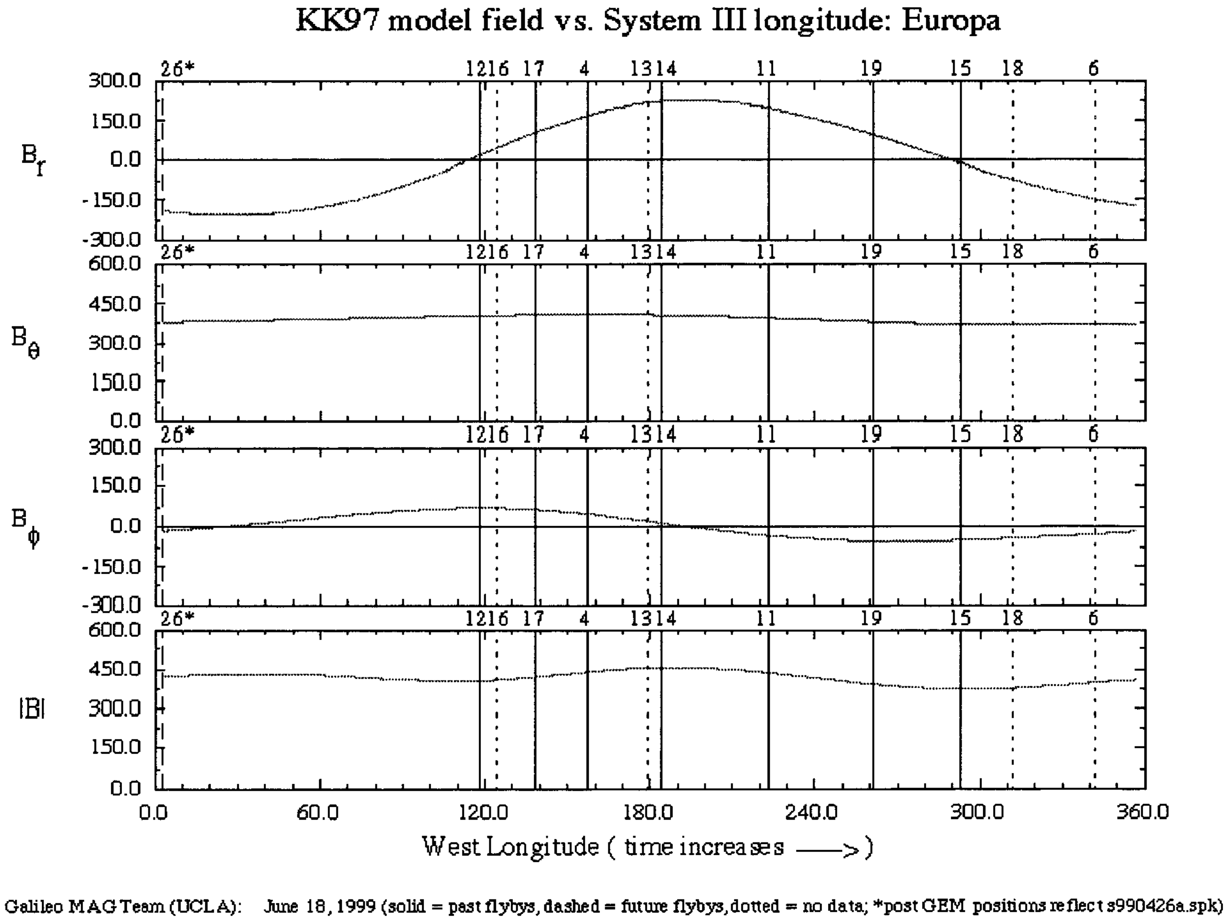


Figure 3 Jupiter Magnetic Field

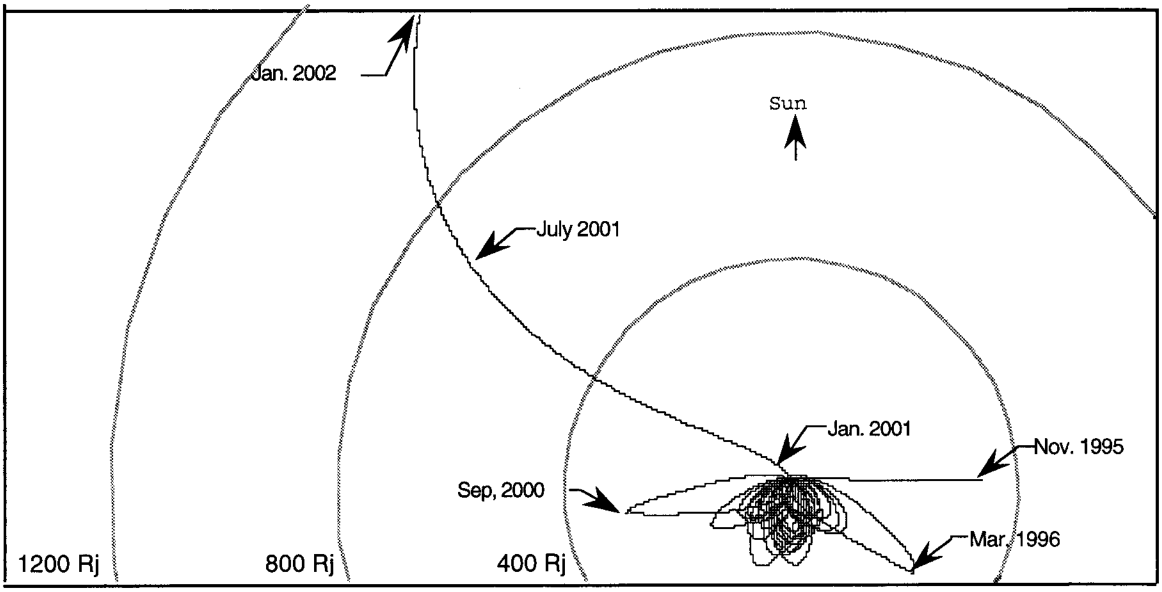


Figure 4 Galileo Satellite Tour from November 1995 to January 2002

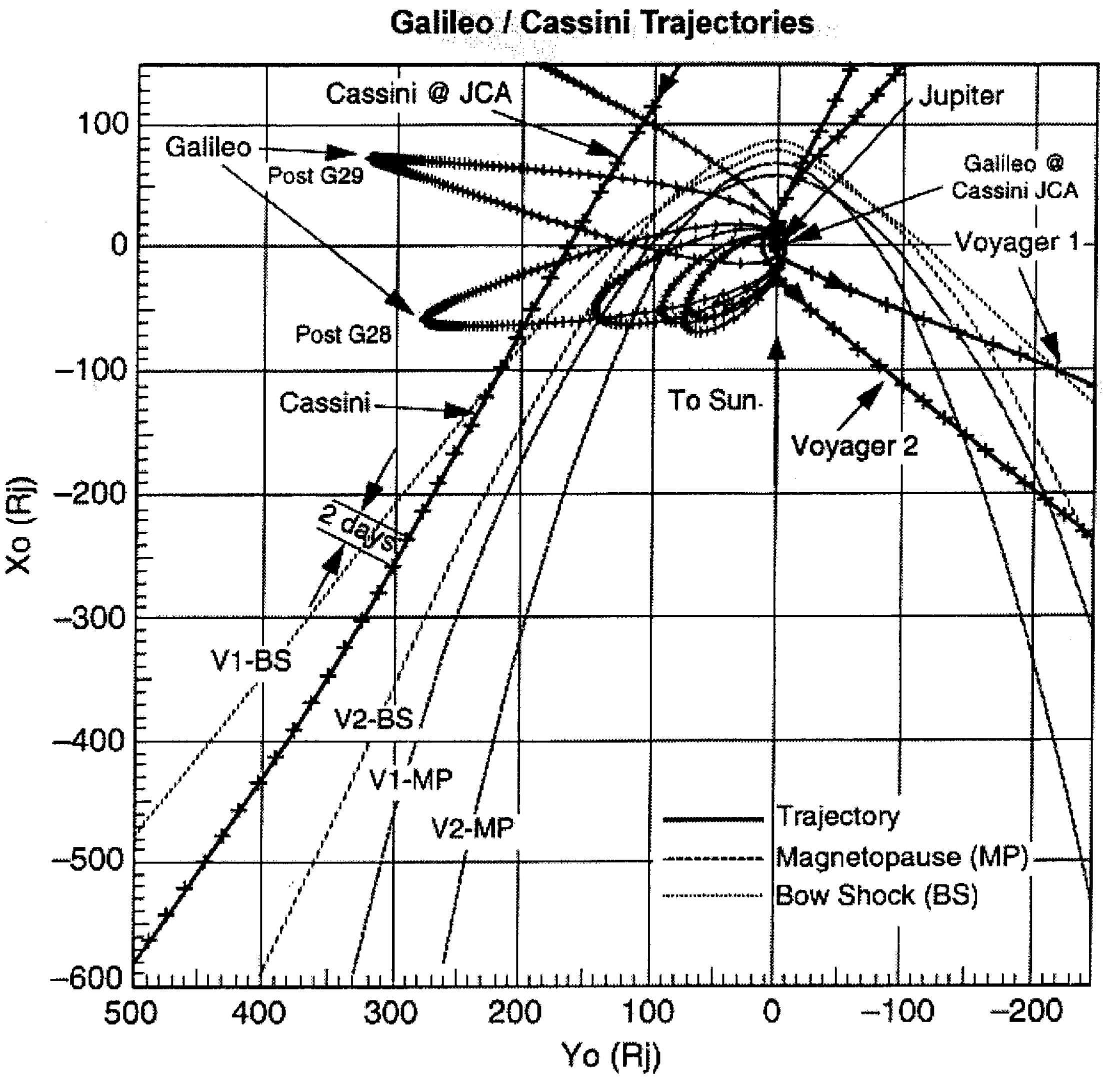


Figure 5 GEM-ex Galileo and Cassini Trajectories

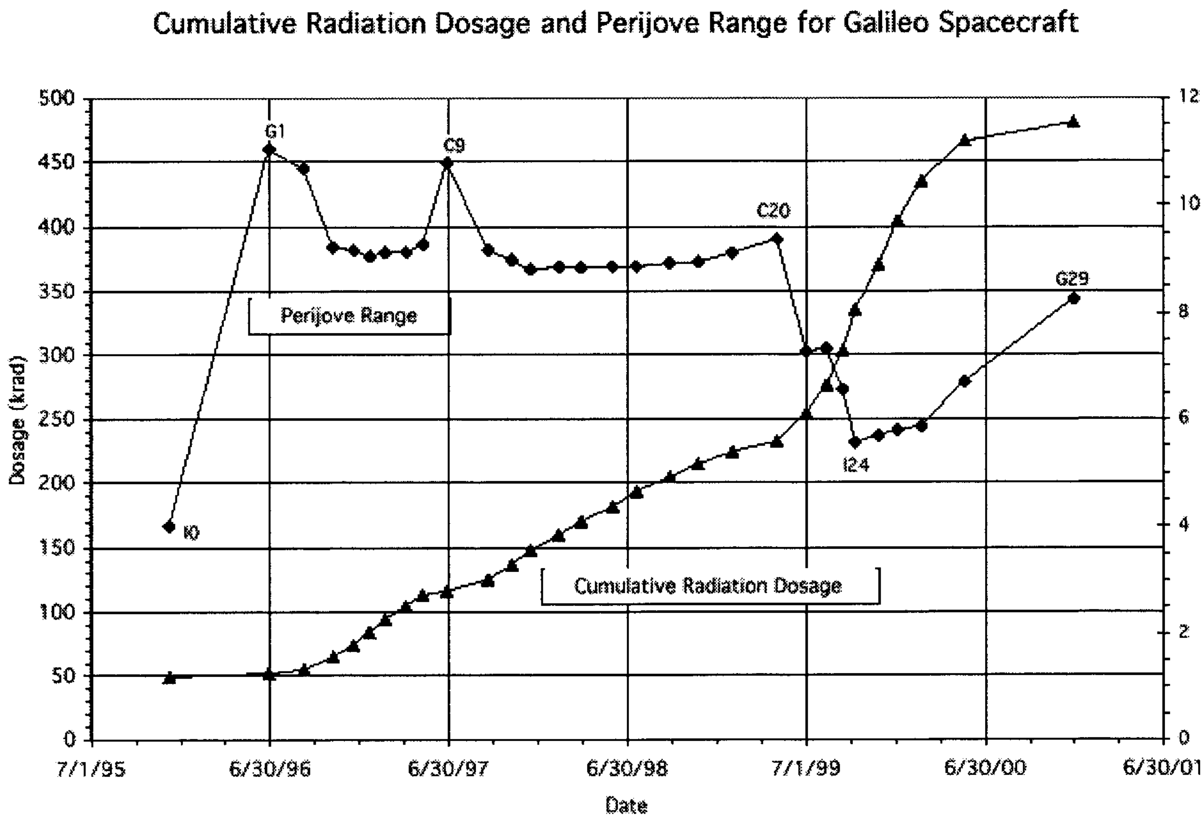


Figure 6 Cumulative Radiation Dosage and Perijove Range for Galileo Since Tour Start